

XMM-Newton discovery of transient X-ray pulsar in NGC 1313

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ABSTRACT

We report on the discovery and analysis of the transient X-ray pulsar XMMU J031747.5-663010 detected in the 2004 November 23 *XMM-Newton* observation of the spiral galaxy NGC 1313. The X-ray source exhibits pulsations with a period $P \sim 765.6$ s and a nearly sinusoidal pulse shape and pulsed fraction $\sim 38\%$ in the 0.3–7 keV energy range. The X-ray spectrum of XMMU J031747.5-663010 is hard and is well fitted with an absorbed simple power law of photon index $\Gamma \sim 1.5$ in the 0.3–7 keV energy band. The X-ray properties of the source and the absence of an optical/UV counterpart brighter than 20 mag allow us to identify XMMU J031747.5-663010 as an accreting X-ray pulsar located in NGC 1313. The estimated absorbed 0.3–7 keV luminosity of the source $L_X \sim 1.6 \times 10^{39}$ ergs s $^{-1}$, makes it one of the brightest X-ray pulsars known. Based on the relatively long pulse period and transient behaviour of the source, we classify it as a Be binary X-ray pulsar candidate. XMMU J031747.5-663010 is the second X-ray pulsar detected outside the Local Group, after transient 18 s pulsating source CXOU J073709.1+653544 discovered in the nearby spiral galaxy NGC 2403.

Key words: X-rays: binaries – (galaxies:) NGC 1313

1 INTRODUCTION

Since their discovery (Giacconi et al. 1971; Tananbaum et al. 1972), accreting X-ray pulsars have been major objects for both observational and theoretical study (White, Swank & Holt 1983; Nagase 1989; Bildsten et al. 1997). The majority of known X-ray pulsars are high-mass binary systems with supergiant or Be donors, clearly associated with younger stellar populations and regions of recent star formation (Charles & Coe 2006).

Traditionally, the study of X-ray pulsars was limited to our Galaxy and neighboring Magellanic Clouds, because of the limited sensitivity and spatial resolution of previous X-ray missions. The advanced capabilities of a new generation of X-ray telescopes (*Chandra* and *XMM-Newton*) have not only caused a rush of new X-ray pulsar discoveries in the Galaxy and Magellanic Clouds (Lutovinov et al. 2005; Chernyakova et al. 2005; Karasev et al. 2008; Haberl & Pietsch 2004; Edge et al. 2004; McGowan et al. 2007), but also opened the possibility to extend X-ray pulsar search to more distant galaxies both inside (Osborne et al. 2001; Trudolyubov et al. 2005; Trudolyubov & Priedhorsky 2008) and beyond the Local Group (Trudolyubov, Priedhorsky & Córdova 2007). The nearby galaxies with recent star formation are especially

suitable candidates for such studies, since they provide the environment in which X-ray pulsars are expected to be plentiful.

The nearby SB(s)d spiral galaxy NGC 1313 at 4.1 Mpc (Méndez et al. 2002), provides an excellent opportunity to study X-ray source populations in a normal galaxy. The overall properties of NGC 1313 are similar to that of irregular Magellanic-type galaxies, and late-type spirals with vigorous recent and ongoing star formation. NGC 1313 was a target of X-ray observations with the *Einstein* (Fabbiano & Trinchieri 1987), *ROSAT* (Colbert et al. 1995; Miller et al. 1998; Schlegel et al. 2000), *ASCA* (Petre et al. 1994), *Chandra* (Schlegel et al. 2004; Zampieri et al. 2004), *XMM-Newton* (Miller et al. 2003; Schlegel et al. 2004; Smith et al. 2007) and *Suzaku* (Mizuno et al. 2007) observatories. These observations uncovered a substantial X-ray source population with three ultraluminous X-ray sources (two accreting binaries and the Type IIn supernova SN 1978K) among them.

In this paper, we report on the discovery of the coherent 765.6 s pulsations in the flux of transient X-ray source XMMU J031747.5-663010 in NGC 1313, using archival data of *XMM-Newton* observations. We study X-ray spectral properties of the source, search for its optical/UV counterparts and discuss its nature.

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2 OBSERVATIONS AND DATA REDUCTION

To study timing and spectral characteristics of XMMU J031747.5-663010, we used the data of 2004 November 23 *XMM-Newton* observation of NGC 1313 field with three European Photon Imaging Camera (EPIC) instruments (MOS1, MOS2 and pn) (Turner et al. 2001; Strueder et al. 2001), and the Optical Monitor (OM) telescope (Mason et al. 2001)(Table 1). We also used several 2000-2006 *XMM-Newton* (Smith et al. 2007) and 2002-2003 *Chandra* observations of the same field to obtain upper limits on the source flux when the source was not detected.

We reduced *XMM* data using *XMM-Newton* Science Analysis System (SAS v 7.0.0)¹. Before generating X-ray images, and source spectra and lightcurves, we performed standard screening of the original event files to exclude time intervals with high background levels, applying an upper count rate threshold of 20% above average background level. The standard SAS tool *barycen* was used to perform barycentric correction on the original EPIC event files used for timing analysis.

We generated EPIC-pn and MOS images of NGC 1313 field in the 0.3-7.0 keV energy band, and used the SAS standard maximum likelihood (ML) source detection script *edetect_chain* to detect and localize point sources. We used bright X-ray sources with known counterparts from USNO-B catalog (Monet et al. 2003) and *Chandra* source lists to correct EPIC image astrometry. The astrometric correction was also applied to the OM images, using cross-correlation with USNO-B catalog. After correction, we estimate residual systematic error in the source positions to be of the order $\sim 1''$ for both EPIC and OM.

To extract EPIC-pn source lightcurves and spectra during the 2004 November 23 *XMM-Newton* observation, we used the elliptical region with semi-axes of $22''$ and $18''$ and position angle of 40° . Due to the source proximity to the edge of EPIC-MOS CCD, the source counts were extracted from the elliptical region with semi-axes of $20''$ and $16''$, including $\sim 70\%$ of the source energy flux. The adjacent source-free regions were used to extract background spectra and lightcurves. The source and background spectra were then renormalized by ratio of the detector areas. For spectral analysis, we used data in the 0.3 – 7 keV energy band. In this analysis we use valid pn events with pattern 0-4 (single and double) and pattern 0-12 (single-quadruple) events for MOS cameras. To synchronize both source and background lightcurves from individual EPIC detectors, we used the identical time filtering criteria based on Mission Relative Time (MRT), following the procedure described in Barnard et al. (2007). The background lightcurves were not subtracted from the source lightcurves, but were used later to estimate the background contribution in the calculation of the source pulsed fractions.

The EPIC spectra were grouped to contain a minimum of 20 counts per spectral bin in order to allow χ^2 statistics, and fit to analytic models using the XSPEC v.12² fitting package (Arnaud 1996). EPIC-pn, MOS1 and MOS2 spectra were fitted simultaneously, but with normalizations

varying independently. For timing analysis we used standard XANADU/XRONOS v.5³ tasks.

The data of *Chandra* observations was processed using the CIAO v3.4⁴ threads. We performed standard screening of the *Chandra* data to exclude time intervals with high background levels. For each observation, we generated X-ray images in the 0.3-7 keV energy band, and used CIAO wavelet detection routine *wavdetect* to detect point sources.

To estimate upper limits on the quiescent source luminosities, the *Chandra*/ACIS and *XMM*/EPIC count rates were converted into energy fluxes in the 0.3-7 keV energy range using Web PIMMS⁵, assuming an absorbed power law spectral shape with photon index $\Gamma = 1.5$ and Galactic foreground absorbing column $N_H = 3.6 \times 10^{20} \text{ cm}^{-2}$.

In the following analysis we assume a distance of 4.1 Mpc for NGC 1313 (Méndez et al. 2002). All parameter errors quoted are 68% (1σ) confidence limits.

3 RESULTS

3.1 Source detection and optical counterparts

A new X-ray source XMMU J031747.5-663010 has been discovered in the data of the 2004 November 23 *XMM-Newton* observation of the NGC 1313 field (Table 1). The estimated source luminosity was $\sim 1.6 \times 10^{39} \text{ ergs s}^{-1}$, assuming the distance of 4.1 Mpc. We measure the position of XMMU J031747.5-663010 to be $\alpha = 03^h 17^m 47.59^s$, $\delta = -66^\circ 30' 10.2''$ (J2000 equinox) with an uncertainty of $\sim 1.0''$ (Fig. 1). The projected galactocentric distance of XMMU J031747.5-663010 is $\sim 3'$ or $\sim 3.6 \text{ kpc}$ at 4.1 Mpc. The analysis of other archival observations of the same field with *XMM-Newton* and *Chandra* did not yield source detection with an upper limit (2σ) ranging from $\sim 2 \times 10^{36}$ to $\sim 2 \times 10^{37} \text{ ergs s}^{-1}$ (or ~ 80 -800 times lower than outburst luminosity), depending on the duration of the observation and instrument used (Table 1).

The search for the optical counterparts using the deep images of NGC 1313 from Las Campanas Observatory 2.5m du Pont telescope (Kuchinski et al. 2000) did not yield stellar-like objects brighter than $\sim 21 \text{ mag}$ in V and $\sim 20 \text{ mag}$ in B band within the 3σ error circle of XMMU J031747.5-663010. We also used the data of the 2004 November 23 *XMM-Newton*/OM observation to search for optical/UV counterparts to the source during its X-ray outburst (Fig. 1). We did not detect any stellar counterparts to XMMU J031747.5-663010 in the OM images down to the limit of $\sim 20 \text{ mag}$ in the V and U bands.

3.2 X-ray pulsations

We performed timing analysis of XMMU J031747.5-663010 using the 2004 November 23 data from all three *XMM-Newton*/EPIC detectors in the 0.3-7 keV energy band. After a barycentric correction of the photon arrival times in the original event lists, we performed a Fast Fourier Transform (FFT) analysis using standard XRONOS task *powspec*, in

¹ See <http://xmm.vilspa.esa.es/user>

² <http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html>

³ <http://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/xronos.html>

⁴ <http://asc.harvard.edu/ciao/>

⁵ <http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html>

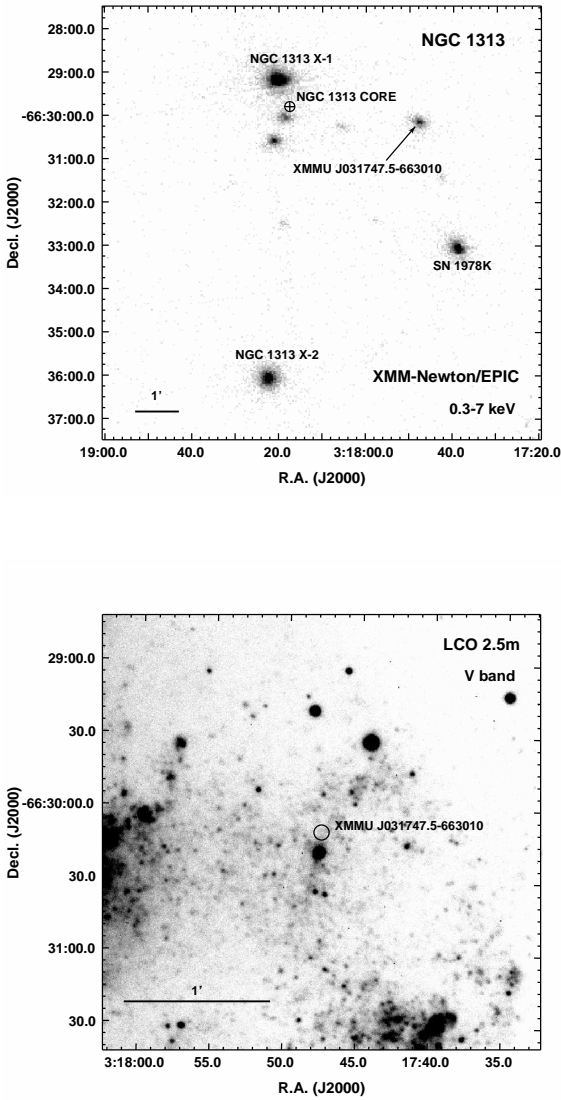


Figure 1. (Upper panel) Combined 0.3-7 keV *XMM*/EPIC image covering a $10' \times 10'$ region of NGC 1313, taken on Nov. 23, 2004. The position of new pulsar XMMU J031747.5-663010 is marked with an arrow, and the position of NGC 1313 nucleus (Ryder et al. 1995) is shown with a cross. Three other bright X-ray sources in the field are also marked for the reference (Schlegel et al. 2000). (Lower panel) Optical V band image of NGC 1313 disk taken with Las Campanas Observatory 2.5m du Pont telescope (Kuchinski et al. 2000). The image is a $3' \times 3'$ square centered on the XMMU J031747.5-663010 position, shown with black circle of $3''$ radius (3σ).

order to search for coherent periodicities. For the analysis of *XMM-Newton* data, we used combined synchronized EPIC-pn and MOS lightcurves with 2.6 s time bins to improve sensitivity. We found strong peak in the Fourier spectrum at the frequency of $\sim 1.3 \times 10^{-3}$ Hz (Fig. 2, upper panel). The strength of the peak in the Fourier spectrum corresponds to the period detection confidence of $\sim 3 \times 10^{-9}$ (Vaughan et al. 1994).

To estimate the pulsation period more precisely, we used an epoch folding technique, assuming no pulse period change

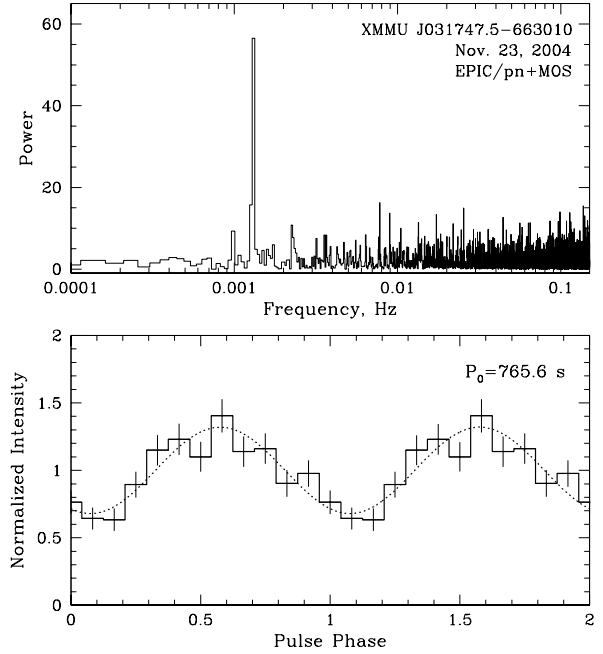


Figure 2. (Upper panel) Power spectrum of XMMU J031747.5-663010 obtained using the data of 2004 Nov. 23 *XMM-Newton*/EPIC (EPIC-pn, MOS1 and MOS2 detectors combined) observation in the 0.3-7 keV energy band. (Lower panel) Corresponding background-corrected source X-ray pulse profile folded with most likely pulsation period (765.6 s). The sinusoidal fit to the pulse profile is shown for comparison with the dotted line.

during 2004 November 23 observation. The most likely value of the pulsation period, 765.6 s (Table 2) was obtained fitting the peak in the χ^2 versus trial period distribution with a Gaussian. The period errors in Table 2 were computed following the procedure described in Leahy (1987). The source lightcurves were folded using the periods determined from epoch folding analysis. The resulting folded lightcurve in the 0.3-7 keV energy band during 2004 November 23 *XMM-Newton* observation is shown in Fig. 2 (lower panel). The source has quasi-sinusoidal pulse profile in the 0.3-7 keV energy band with a pulsed fraction of $38 \pm 3\%$. The pulsed fraction was defined as $(I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$, where I_{\max} and I_{\min} represent source intensities at the maximum and minimum of the pulse profile, excluding background photons.

To investigate energy dependence of the source pulse profile, we extracted light curves in the soft (0.3-2 keV) and hard (2-7 keV) bands for 2004 Nov. 23 observation, and folded them at the corresponding best pulsation period (Fig. 3). Both bands show quasi-sinusoidal pulse profiles. Because of the relatively poor statistics, we could detect only marginal difference between source pulse profiles at low and high energies, which have background-corrected pulsed fractions of $34 \pm 4\%$ and $40 \pm 4\%$.

3.3 X-ray spectra

The pulse phase averaged *XMM-Newton*/EPIC spectra of XMMU J031747.5-663010 can be adequately fit with the absorbed simple power law model with photon index, $\Gamma \sim 1.5$

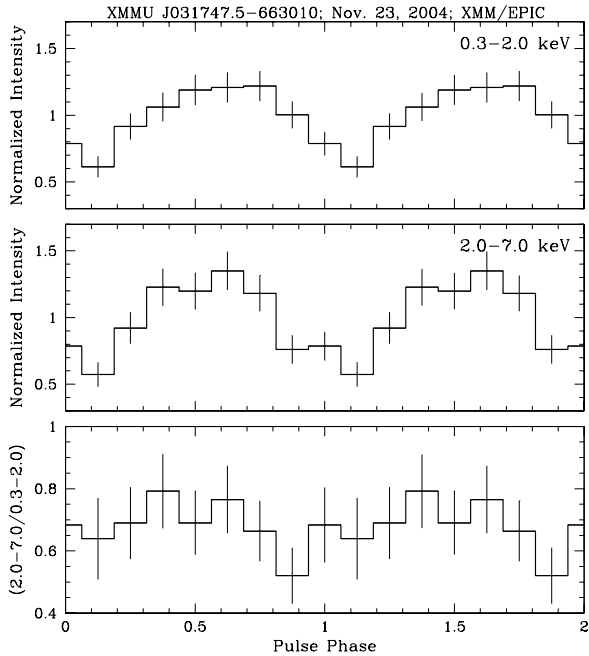


Figure 3. Normalized X-ray lightcurves of XMMU J031747.5-663010 folded at the best pulsation period in the soft (0.3-2 keV, upper panel) and hard (2-7 keV, middle panel) energy bands along with hardness ratio (lower panel), computed taking background contribution into account.

and an equivalent hydrogen density $N_H \sim 2.3 \times 10^{21} \text{ cm}^{-2}$. The corresponding absorbed luminosity of the source in the 0.3-7 keV band is $\sim 1.6 \times 10^{39} \text{ ergs s}^{-1}$, assuming the distance of 4.1 Mpc. The best-fit spectral model parameters of the source are given in Table 2. The measured absorbing column N_H is ~ 6 times higher than the Galactic hydrogen column in the direction of NGC 1313, $3.6 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990), consistent with an additional intrinsic absorption within the system and inside the disk of NGC 1313.

4 DISCUSSION

The absence of the bright optical counterpart to XMMU J031747.5-663010, its overall X-ray properties (spectrum, pulsations, transient behaviour), and positional coincidence with NGC 1313 disk, allow us to conclude that it should be located outside our Galaxy and probably belongs to NGC 1313. The X-ray pulsations and energy spectrum of XMMU J031747.5-663010 imply that it is almost certainly an accreting highly-magnetized neutron star in a high-mass binary system (White, Swank & Holt 1983; Nagase 1989). The association with NGC 1313 makes this source an extremely bright object with luminosity $L_X \sim 1.6 \times 10^{39} \text{ ergs s}^{-1}$, greatly exceeding the isotropic Eddington luminosity limit for a $1.4 M_\odot$ neutron star accreting hydrogen-rich material.

The relatively long pulse period of XMMU J031747.5-663010 (765.6 s) places it among the systems with a companion that is either a supergiant or a Be star on a Corbet diagram (Corbet 1986). The transient behavior of the source lends support to the interpretation of this source as yet an-

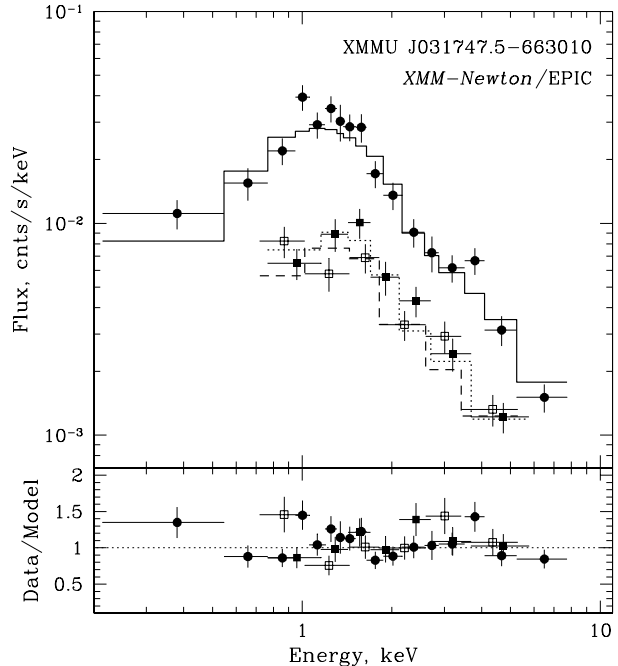


Figure 4. EPIC count spectra and model ratios of XMMU J031747.5-663010 during the 2004 Nov. 23 observation. The EPIC-pn data is plotted with filled circles, while EPIC-MOS1 and MOS2 data is shown with filled and open squares respectively. The best-fit absorbed power law model approximation of EPIC-pn, MOS1 and MOS2 data is shown with solid, dotted and dashed histograms.

other Be binary, since the majority of Be systems display recurrent/transient outbursts. An extremely high luminosity of the source still falls into the luminosity range observed in the Be X-ray pulsars, with one system, A0538-66 known to reach similar luminosity during its giant (Type II) outburst (White & Carpenter 1978; Skinner et al. 1982). The high luminosity of XMMU J031747.5-663010 is also consistent with theoretical predictions for super-Eddington accretion onto highly magnetized ($B \gtrsim 10^{12} \text{ G}$) neutron star (Basko & Sunyaev 1976).

The high-mass nature of the system implies its relatively young age, consistent with its location within one of the spiral arms of NGC 1313 (Fig. 1). Since the Be interpretation still remains preliminary, optical identification is essential to determine the nature of the system. For optical identification, deeper optical observations are needed. The follow-up monitoring observations with *Chandra* and *XMM-Newton* are needed to test if it shows recurrent outbursts. Future X-ray observations of XMMU J031747.5-663010, if it reappears, could improve source localization and study long-term evolution of its X-ray properties and X-ray pulsation.

XMMU J031747.5-663010 is the second X-ray pulsar detected outside the Local Group, after 18 s pulsating X-ray source CXOU J073709.1+653544 in the nearby spiral galaxy NGC 2403 (Trudolyubov, Priedhorsky & Córdova 2007). Both sources are extremely bright transient systems with total luminosities $\gtrsim 10^{39} \text{ ergs s}^{-1}$, and probably belong to a rare class of most luminous Be binary X-ray pulsars. Similar systems can be detected and studied effectively with a series of moderately deep (10-50 ks) monitoring *XMM-*

Table 1. XMM-Newton and Chandra observations of NGC 1313 used in the analysis of XMMU J031747.5-663010.

Date, UT	Obs. ID	Instrument	Mode/ Filter	RA (J2000) ^a (h:m:s)	Dec (J2000) ^a (d:m:s)	Exp. ^b (ks)	Source luminosity ^c (ergs s ⁻¹)
2000 Oct. 17	0106860101	EPIC	Full/Medium	03:18:22.61	-66:30:36.4	21.6(MOS)/21.6(pn)	$< 4.1 \times 10^{36}$
2002 Oct. 13	2950	ACIS-S	Very Faint	03:18:32.00	-66:31:10.0	19.9	$< 2.9 \times 10^{36}$
2002 Nov. 09	3550	ACIS-I	Very Faint	03:17:55.00	-66:34:40.0	14.5	$< 4.0 \times 10^{36}$
2003 Oct. 02	3551	ACIS-I	Very Faint	03:17:55.00	-66:34:40.0	14.8	$< 3.2 \times 10^{36}$
2003 Dec. 21	0150280301	EPIC	Full/Thin	03:18:20.30	-66:37:03.2	10.0(MOS)/8.4(pn)	$< 1.4 \times 10^{37}$
2003 Dec. 23	0150280401	EPIC	Full/Thin	03:18:19.69	-66:37:02.0	7.5(MOS)/6.2(pn)	$< 1.8 \times 10^{37}$
2003 Dec. 25	0150280501	EPIC	Full/Thin	03:18:19.26	-66:37:01.3	8.6(MOS)/7.0(pn)	$< 2.0 \times 10^{37}$
2004 Jan. 08	0150280601	EPIC	Full/Thin	03 18 16.60	-66 36 56.1	10.9(MOS)/9.5(pn)	$< 1.4 \times 10^{37}$
2004 Jan. 16	0150281101	EPIC	Full/Thin	03:18:14.90	-66:36:51.6	8.6(MOS)/7.0(pn)	$< 1.7 \times 10^{37}$
2004 Aug. 23	0205230401	EPIC	Full/Thin	03:18:31.90	-66:35:33.1	12.1(MOS)/11.2(pn)	$< 1.7 \times 10^{37}$
2004 Nov. 23	0205230501	EPIC	Full/Thin	03:18:25.09	-66:36:59.5	15.6(MOS)/14.0(pn)	1.6×10^{39}
2004 Jun. 05	0205230301	EPIC	Full/Thin	03:18:19.98	-66:34:48.8	11.6(MOS)/10.0(pn)	$< 1.1 \times 10^{37}$
2005 Feb. 07	0205230601	EPIC	Full/Thin	03:18:12.06	-66:36:31.1	12.4(MOS)/10.9(pn)	$< 1.4 \times 10^{37}$
2006 Mar. 06	0301860101	EPIC	Full/Medium	03:17:27.38	-66:33:08.0	21.5(MOS)/19.9(pn)	$< 7.1 \times 10^{36}$
2006 Oct. 15	0405090101	EPIC	Full/Thin	03:18:23.51	-66:30:38.9	100.0(MOS)/98.0(pn)	$< 2.3 \times 10^{36}$

^a – pointing coordinates^b – instrument exposure used in the analysis^c – estimated luminosity of XMMU J031747.5-663010 in the 0.3-7 keV band**Table 2.** X-ray pulsation parameters and spectral fit information for XMMU J031747.5-663010.

Timing Parameters			POWERLAW*WABS Spectral Model Parameters						
Period (s)	PF _{0.3–7keV} (%) ^a	N _H ($\times 10^{20}$ cm ⁻²)	Photon Index	Flux _{abs} ^b	Flux _{abs,corr} ^c	L _{abs} ^d	L _{abs,corr} ^e	χ^2 (d.o.f.)	Instrument
765.6 \pm 4.0	38 \pm 3	23 \pm 4	1.48 ^{+0.10} _{-0.09}	7.84 \pm 0.35	9.98 ^{+0.55} _{-0.52}	1.58	2.01	64.9(52)	pn+M1+M2

^a – pulsed fraction in the 0.3 – 7 keV energy band^b – absorbed model flux in the 0.3 – 7 keV energy range in units of 10^{-13} erg s⁻¹ cm⁻²^c – unabsorbed model flux in the 0.3 – 7 keV energy range in units of 10^{-13} erg s⁻¹ cm⁻²^d – absorbed luminosity in the 0.3 – 7 keV energy range in units of 10^{39} erg s⁻¹, assuming the distance of 4.1 Mpc^e – unabsorbed luminosity in the 0.3 – 7 keV energy range in units of 10^{39} erg s⁻¹, assuming the distance of 4.1 Mpc

Newton and *Chandra* observations up to the distances of several Mpc. Therefore, the detailed analysis of the existing archival and new observations of nearby spiral and irregular galaxies have a potential to significantly increase statistics of these systems and provide us with better understanding of their nature and connection to the underlying stellar population.

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